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Matching Simulated Fracture Data with Field Measurements Using Joint Intensity

Judy Ehlen

U.S. Army Topographic Engineering Center
7701 Telegraph Road
Alexandria, Va., U.S.A.

ABSTRACT

Three-dimensional models of fracture patterns were generated using different measures of joint intensity (λ), a measure of joint surface area per unit volume. The simulated data were compared to field measurements and the models were regenerated until the two matched as close as possible. Mean vertical joint spacing was used for the comparison. Because only a sample of trace lengths was measured in each outcrop, λ was initially defined for each joint set as nl/hw, where n = number of joints, and l = mean trace length, h = sampling area height, and w = sampling area width . Simulated mean vertical joint spacings using this definition were signi-ficantly lower than the means for the field measurements. Mean simulated vertical spacing is 0.12 m, whereas mean measured vertical spacing is 0.23 m, indicating that λ at 12.10 is too high. Consequently, the definition of λ was reevaluated. Sampling area widths varied for each joint set in each outcrop, so joint set intensities were weighted proportionally with respect to sampling area width. Joint intensities for the horizontal sets were recalculated using the length of the longest joint in that set as the sampling area height. In addition, the second set of models was generated in increasing termination percent order which better represents geologic conditions. Mean simulated intensity for these models is 7.34, and mean simulated vertical spacing is 0.20 m. These results are realistic with respect to the field data.

KEYWORDS

Joint intensity, joint trace length, joint spacing, weathered granite, 3-D modelling, termination percent

INTRODUCTION

Joint intensity (λ), a three-dimensional measure, is a difficult parameter to determine because joints can rarely be viewed in three dimensions. Consequently, joint intensity is typically addressed as a measure of either joint trace length or joint spacing. The data used for estimation are usually one-dimensional borehole or line survey data, or two-dimensional fracture trace maps.

Definitions of joint intensity vary with usage or application, and according to the type of data available. Definitions noted by Priest and Hudson (1976) include the number of discontinuities per unit volume, and the number of discontinuities per unit distance measured perpendicular to the strike of the discontinuities. Baecher *et al* (1977) define joint density as the number of joint centers per unit volume of rock, and joint intensity as joint surface area per unit volume. Dershowitz and Einstein (1988) provide three definitions: the number of joints per unit area or volume, total joint trace length per unit area, and total joint area per unit volume. Wheeler and Dixon (1980), on the other hand, estimated three-dimensional joint intensity directly from joint spacing data and determined that other parameters are not needed.

In this study, three-dimensional models of fracture patterns were generated using FracMan, the Golder Associates program for interactive discrete feature data analysis, geometric modeling, and exploration simulation (Dershowitz *et al*, 1995). Three measures of joint intensity can be used in FracMan: the number of fractures to be generated, the areal intensity, and the volume percent. Areal intensity, typically total joint trace length divided by sampling area, is the preferred measure because it is invariant with respect to the fracture size distri-bution (Dershowitz *et al*, 1995). This study identifies difficulties that may be encountered using parameter definitions such as these, yet shows that nonstandard data and a more geologic approach can produce high quality results.

SAMPLE SITES

An areal sampling scheme was used to collect the field data in three areas in weathered granite. Joint spacing and orientation were measured for the most persistent joint sets in multiple outcrops in each area. Spacings were measured for primary and secondary joints (Ehlen, 1989). A primary joint is a long, usually open, outcrop-shape-controlling joint that cuts across other joint traces. Primary joints typically extend through the outcrop. A secondary joint is a shorter joint, local in extent, that typically terminates against other joints. In addition, a sample of trace lengths for primary and secondary joints was measured for each set, and termination percent (T intersections) was estimated for most secondary joint sets; termination percent for primary joint sets is by definition 0.

Area 1 consists of two outcrops. Outcrop 1A, in part a natural outcrop, is composed of moderately weathered granite with a small amount of highly weathered granite around the edges. Data were collected from two steeply dipping joint sets and one horizontal joint set. Outcrop 1B, a road cut, consists of completely weathered granite. It contains two steeply dipping joint sets. Joint data were also collected from two outcrops in Area 2. Both are cut faces consisting of moderately weathered granite cores surrounded by highly weathered granite. In Outcrop 2A, the proportion of moderately weathered granite exceeds that of highly weathered granite. The opposite is true for Outcrop 2B, the majority of which is highly weathered granite. Data were collected from three steeply dipping joint sets in Outcrop 2A, and from two steeply dipping joint sets in Outcrop 2B. Area 3 consists of four outcrops, one of which is a cut face, the others being road cuts. Outcrop 3A, the cut face, consists primarily of highly weathered granite with a core of moderately weathered granite. It contains two steeply dipping joint sets, one horizontal joint set, and one inclined joint set. Outcrops 3B, 3C, and 3D consist only of highly weathered granite. Data were collected from one steeply dipping joint set, one horizontal joint set, and one inclined joint set in Outcrop 3B; from three steeply dipping joint sets in Outcrop 3C; and from two steeply dipping joint sets and one horizontal joint set in Outcrop 3D. Outcrop size, sampling area, and the persistence of the individual joint sets varied at each sampling site. Table 1 lists the field data with calculated joint intensities and sampling area sizes.

MODELING

Initial Models

The field data were first modeled outcrop by outcrop using the BART (Baecher Algorithm, Revised Termina-tions; Dershowitz *et al*, 1995) model. The primary joints in each set were generated immediately before the secondary

joints in that set, in the order in which the measurements were made in the field. Each three-dimensional model was sampled using a simulated vertical trace plane oriented in the same direction as the line of measurement in the field, parallel to the outcrop face, so that comparisons could be made with outcrop photographs. Model intensities were compared to joint intensities calculated from the field data, and simulated joint spacings were compared to joint spacings measured in the field. Simulated joint spacings were determined

TABLE 1

FIELD MEASUREMENTS AND CALCULATED JOINT INTENSITIES AND SAMPLING AREAS

	Joint set	# primary joints	# secondary joints	Line length (m)	Mean length primary joints (m)	Mean length secondary joints (m)	Sampling area (m^2)	Primary joint intensity	Secondary joint intensity	Secondary joint termination percent*
Area 1										
Outcrop 1A	1	8	90	17.3	4.6	0.69	51.90	0.71	1.20	75
	2	2	12	1.81	6.5	0.7	5.43	2.39	1.55	75
	3	2	96	26.6	-	0.59	79.80	-	0.71	75
Outcrop 1B	4	0	144	28.2	-	1.2	141	-	1.23	50
	5	0	38	10.3	-	0.9	41.2	-	0.83	50
Area 2										
Outcrop 2A	1	8	127	10.4	3.1	0.67	26.00	0.95	3.27	0
	2	0	96	10.3	-	0.58	25.75	-	2.16	100
	3	1	35	2.7	2.5	0.45	6.75	0.37	2.33	10
Outcrop 2B	4	1	82	21.4	12	1	107	0.11	0.77	75
	5	0	95	21.4	10	1	107	-	0.89	75
Area 3										
Outcrop 3A	1	0	60	5.5	-	0.57	18.70	-	1.83	50
	2	2	37	3.4	4.5	2.5	25.50	0.35	3.63	50
	3	3	61	10.1	4.8	1.5	34.34	0.42	2.66	30
	4	0	39	5.5	-	0.87	18.70	-	1.81	100
Outcrop 3B	5	12	90	35	2.6	0.8	94.50	0.33	0.76	75
	6	3	33	9.2	5	2.2	24.84	0.60	2.92	75
	7	1	20	2.7	2.6	0.63	13.77	0.19	0.92	75
Outcrop 3C	8	2	28	5	3.5	1.1	20.00	0.35	1.54	50
	9	2	69	11.9	2.4	0.62	23.80	0.20	1.80	20
	10	3	55	8.7	3.3	0.68	17.40	0.57	2.15	50
Outcrop 3D	11	8	101	22.1	3.7	0.86	229.84	0.13	0.38	30
	12	3	85	19.2	4	1.3	199.68	0.06	0.55	70
	13	1	21	10.4	10.5	2.6	208.00	0.05	0.26	50

* Termination percent for primary joints is by definition 0.

by sampling the models using two sets of multiple simulated boreholes that were perpendicular and parallel to the top surface (the "ground surface") of the model, respectively. The diameter of NX core was used for the simulated boreholes. The modelling process was repeated with slight "tweaking" of the input data until the trace plane looked

as much like the out-crop face as possible, and the simulated intensities and spacings were as similar as possible to the field data. "Tweaking" consisted primarily of changing estimates of termination percent using photographs of sites for which field estimates were not made. When the best match had been made between field data and simulated data for each outcrop, the data for the outcrops in each sampling area were combined to produce aggregate models for each of the three areas. The data for the outcrops were entered consecutively in field data collection order to produce the area models. The modelling process, e.g., input required, distributions used, is discussed in greater depth in Ehlen (1996).

The areal intensity measure defined by Dershowitz *et al* (1995) is calculated as:

$$\lambda = L/hw \qquad (1)$$

where L = total joint trace length, h = sampling area height, and w = sampling area width for each joint set. Joint intensity is additive, so the intensities for each set in an outcrop were summed to determine intensity for the area model. Because, as noted above, only a sample of primary and secondary joint trace lengths was meas-ured in each outcrop, so this definition was not used in this study. Thus, λ was initially defined as:

$$\lambda = nl/hw \qquad (2)$$

where n = total number of primary or secondary joints in a set, l = mean primary or secondary trace length for that set, h = sampling area height, and w = sampling area width. Sampling area height for vertical joints in each outcrop was determined by summing horizontal joint spacings if horizontal joints were present, or by actual measurement. The simulated results using this measure of joint intensity are compared to calculated intensities in Table 2. Simulated and measured mean vertical joint spacings also are shown in Table 2. Figure 1 is an example of a vertical trace plane, 20 m on a side, through the three-dimensional model of Area 3.

TABLE 2

JOINT INTENSITIES AND VERTICAL JOINT SPACINGS USING $\lambda = nl/hw$

	Area 1	Area 2	Area 3
Joint Intensity			
Calculated intensity	7.84	11.29	7.15
Simulated intensity	7.71	11.30	17.00
Mean Vertical Joint Spacing			
Measured spacing	0.22	0.16	0.31
(standard deviation)	(0.26)	(0.28)	(0.74)
Simulated spacing	0.16	0.10	0.09
(standard deviation)	(0.02)	(0.01)	(0.03)

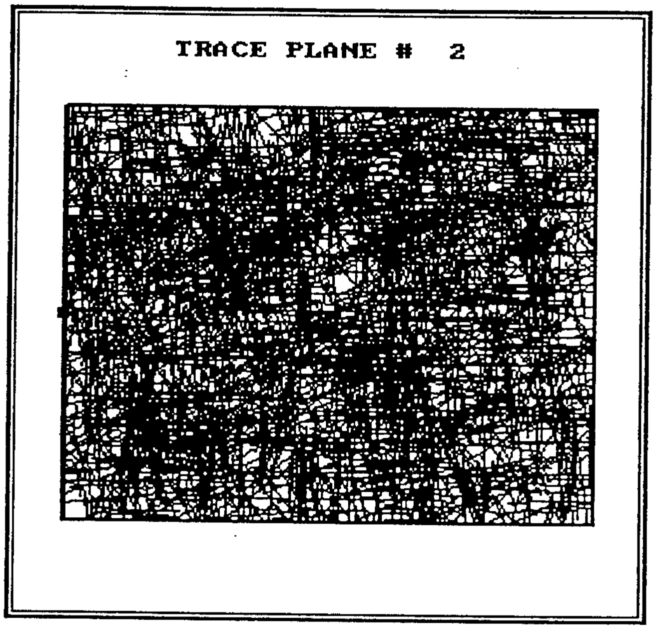

Figure 1. 20x20 m vertical trace plane through the three-dimensional model of Area 3.

The simulated mean joint spacings for all three models are significantly lower than the means for the field measurements. Simulated mean vertical joint spacings range from 29% to 73% of the mean joint spacings for the field data. The simulated joint spacings, however, are within the standard deviations for the field measurements at the 95% confidence level. For the three areas combined, mean simulated vertical joint spacing is 0.12 m, whereas mean vertical joint spacing for the field data is 0.23 m. Although the simulated intensities were very similar to the intensities calculated for the field data, the discrepancy between measured and simulated vertical joint spacings indicates that the intensities used to generate the models were too high. Consequently, the definition of λ was reevaluated.

Final Models

The widths of individual joint sets in an outcrop vary. This explains in part why the initial intensities were too high and the joint spacings too small. For a given outcrop in the initial models, the intensities for "short" joint sets were treated as equal to intensities for "long" joint sets, which they are not. For example, if the intensity for a joint set were 3.4, the line length, 5.0 m, and the sampling area width, 10 m, this set would be simulated with an intensity of 3.4 for the entire 10 m, which in effect doubles the intensity of that set. Consequently, verti-cal joint intensities were weighted with respect to sampling area width. Intensities for joint sets that did not extend the full width of the sampling area were weighted proportionally to that width. For example, if the sampling area were 22.1 m wide, and the joint set 10.4 m in length, the proportionality factor would be 2.13, and λ would be calculated as:

$$\lambda = (nl/hw)/p \tag{3}$$

where p is the proportionality factor (sampling area width/joint set length) for that set; n, l, h and w are as defined above. The initial intensity for this joint set using Eqn. 2 is 0.05, whereas the weighted intensity using Eqn. 3 is 0.02.

Intensities for horizontal joint sets are always significantly greater than intensities for vertical joint sets. For example, secondary joint intensities for horizontal joint sets in Outcrop 3A (see Table 1), are 3.63 and 2.66, whereas the intensities for the steeply dipping joints sets are 1.83 and 1.81. This is not only because sampling area widths were often arbitrary estimates, but also because sampling areas for horizontal joints were selected to maximize the number of measurements. Because the outcrops were usually longer than they were tall, it was difficult to collect an adequate sample of horizontal joint spacings. Consequently, horizontal joint spacings tended to be measured where these joints were relatively abundant compared with other parts of the outcrop. Horizontal joint spacing distributions thus are biased toward the more closely spaced joints. Weighting by sampling area width, as was done for vertical joint sets, was not possible because spacings were measured for only one horizontal joint set in each outcrop (most outcrops contained only one horizontal set, if that), so inten-sities for the horizontal sets were recalculated using the length of the longest joint in that set as the sampling area height.

The weighted intensities are shown in Table 3. Termination percent for each joint set also is shown because some were changed from those used in the initial models. The joint set number is shown so that direct comparisons can be made with the data in Table 1. As with Table 1, Table 3 shows the joint sets in the order in which they were generated: the Table 3 order is very different from that in Table 1. For the new models, the joint sets were generated in increasing termination percent order because this order more likely represents the order in which the joints were formed. As joints propagate, longer joints shield shorter joints, and as the length ratios increase, the propagation energy of shorter joints drops toward 0, producing the typical joint set with few long joints and many short joints (Segall and Pollard, 1983; Pollard and Aydin, 1988). In addition, termination percent for each successive joint set must necessarily increase because there are more joints against which to terminate. As in the initial models, primary joints were generated before secondary joints; however, they were generated as a group, and in order of second-ary joint termination percent, rather than arbitrarily, joint set by joint set.

TABLE 3

WEIGHTED JOINT INTENSITIES AND REVISED SECONDARY JOINT TERMINATION PERCENTAGES

	Joint Set	Primary joint intensity	Secondary joint intensity	Secondary joint termination percent
Area 1	4	-	2.45	0
	5	-	0.48	0
	1	0.55	0.93	30
	3	-	0.85	30
	2	0.20	0.13	100
Area 2	1	0.95	3.27	0
	5	0.10	0.61	10
	2	0.11	0.77	50
	3	-	0.89	50
	4	-	2.14	100
Area 3	2	0.17	0.95	0
	1	-	0.63	10
	9	0.13	0.29	10
	13	0.10	0.39	10
	3	0.06	0.58	30
	12	0.12	0.51	30
	11	0.12	0.34	30
	4	0.02	0.12	40
	5	0.10	0.76	40
	6	0.05	0.33	80
	7	0.06	0.27	100
	10	0.19	0.93	100
	8	-	0.29	100

As can be seen in Table 4, the results using the weighted intensities and a more geologic generation order are much more like the mean joint spacings measured in the field than those from the initial models. Simulated mean vertical joint spacings range from 84% to 95% of the mean joint spacings for the field data. Mean simulated intensity for these three models at 7.34 is 61% lower than the mean simulated intensity of 12.10 for the initial three models. Mean simulated vertical joint spacing for the three new models combined is 0.20 m, much closer to the 0.23 m mean for the three field areas. Mean simulated spacings for two of the three models are within 7% of the field measurements. Figure 2 shows a simulated vertical trace plane, 15 m on a side,

TABLE 4

INTENSITIES AND VERTICAL JOINT SPACINGS USING THE WEIGHTED INPUT DATA

	Area 1	Area 2	Area 3
Joint Intensity			
Calculated intensity	5.59	8.84	7.62
Simulated intensity	5.59	8.83	7.62
Mean Vertical Joint Spacing			
Measured spacing	0.22	0.16	0.31
(standard deviation)	(0.26)	(0.28)	(0.74)
Simulated spacing	0.21	0.15	0.26
(standard deviation)	(0.05)	(0.02)	(0.12)

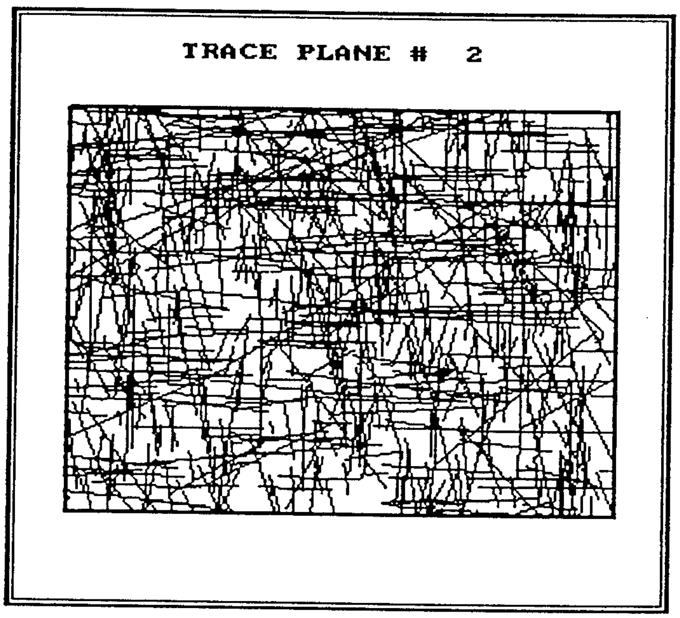

Figure 2. 15x15 m vertical trace plane through the final three-dimensional model of Area 3.

through the three-dimensional model of Area 3 generated using the weighted intensities. When compared with Figure 2, the difference in intensities between the two simulated trace planes is apparent.

DISCUSSION

"Tweaking"

As noted above, each time a model was generated for an outcrop, the input data, particularly termination per-cent, were "tweaked" (usually increased) in an attempt to produce simulated results more like the field data. Other changes in input data included estimating mean joint trace lengths for joints sets where trace lengths were not

measured: this was done by using the means of the mean trace lengths for the other joint sets in that outcrop. Each time a change was made in one variable, the simulated results changed slightly for other variables, with the exception of joint intensity, which remained virtually unchanged. For example, field estimates of termina-tion percent were used in the first models. Where there were no estimates, 0 was used. The resulting simulated mean vertical joint spacings were very small, so in the next realization, termination percents were increased and positive values based on analysis of outcrop photographs were used for joint sets where estimates had not been made in the field. This increased mean simulated joint spacing (e.g., joint spacing became wider) and also affected mean simulated trace length, generally reducing it. As termination percent increased, simulated mean joint spacing continued to increase (become wider), but only up to a point. At about 70% termination (this value was slightly different for each joint set), mean simulated spacing began to decrease, and continued to do so as termination percent was further increased. Even at the point where mean simulated joint spacing was at its widest, however, simulated joint intensities showed little change.

Joint Trace Lengths

Much time and effort have been spent by many researchers to portray joint characteristics in a rock mass. These attempts have resulted in the development of relatively standard methodologies for collecting joint data in the field (the line survey method and areal sampling schemes) and for statistical approaches to characterizing the data to obtain a three-dimensional perspective of discontinuities in the rock mass. These data are typically collected in either one or two dimensions (boreholes and outcrops, respectively), and it is difficult to extrapolate these data to the third dimension. Bias results from the fact that one collects a sample in the field, often of inadequate proportions, and then attempts to define the population distribution from that sample. Biases in orientation data collected using the line survey technique are relatively easy to correct (Terzaghi, 1965), but correction of biases for spacing and trace length measurements are another matter. Because joint spacing data are not used as input to three-dimensional modelling in FracMan, joint spacing biases and their correction and the statistical characteristics of joint spacing distributions will not be discussed further.

Joint trace length data are subject to two types of bias, truncation and censoring (Baecher and Lanney, 1977). Truncation means that short trace lengths are usually not measured. This is partly related to the difficulty of seeing very short joints, but more importantly, most workers select a minimum length for measurement. Trun-cation is not as great a problem in this study as in many others because no minimum length cutoff was used, although the sample of trace lengths measured probably did not include an adequate proportion of the very shortest trace lengths. Censoring refers to the absence of one or both ends of the fracture trace within the out-crop. This problem affects both primary and secondary joints, but is especially important with respect to pri-mary joints, which, by definition, extend through the outcrop. Any sample of trace lengths thus will be biased toward the shorter joints in that population (Baecher, 1983).

A number of solutions are described in the literature for truncation and censoring (e.g., Cruden, 1977; Priest and Hudson, 1981; La Pointe and Hudson, 1985; Kulatilake *et al*, 1993). However, no corrections were made on these data, although the problem was recognized. First, only a small sample of trace lengths was measured for each joint set. One hopes this sample is representative, but because this is unlikely, use of a formal procedure to correct the data seemed fruitless. Second, the position of any measured fracture trace on a three-dimensional joint is unknown. The trace could be a short section near the edge, or it could be the true diameter. Thus it seemed pointless to make geometric corrections if the geometry is unknown. Finally, and perhaps most impor-tant, FracMan requires mean joint radius for each joint set as input to the modelling process. This parameter was calculated using a first approximation [(0.05*mean length) + standard deviation; personal communication, W.S. Dershowitz, 1995], so a difference of a few centimeters in mean trace length was unlikely to affect the result.

CONCLUSIONS

The standard definition of areal intensity, total joint trace length per unit area, could not be used in this study because only a sample of trace lengths was measured for each joint set. Instead, mean trace length for each joint set was multiplied by the number of joints in that set. Although this measure of joint intensity produced simulated intensities similar to those calculated using the field data, the mean simulated vertical joint spacings in these initial models were significantly lower than mean vertical joint spacings measured in the field. Conse-quently, joint intensities for each joint set were weighted according to the proportion of the outcrop occupied by that set, and the input data were ordered to more realistically reflect geologic conditions, based on termination percent. Weighting resulted in reduced intensities; the simulated intensities again being very similar to those calculated from the field data. The simulated vertical joint spacings in these models were acceptably similar to those measured in the field.

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